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Progress in the Development of All-Back-Contacted Silicon Solar Cells

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Abstract

N-type all-back-contact (ABC) silicon solar cells incorporating a simple oxide-nitride passivation scheme are presently being developed at the Australian National University. Having already achieved promising efficiencies with planar ABC cells [1], this work analyses the cell performance after integrating a surface texturing step into the process flow. Although the textured cells have significantly lower front surface reflection, the measured short-circuit current density is actually lower than that of the planar cells. Photoconductance decay data indicate the presence of high carrier recombination at the textured surface of the ABC cells, which are deposited with a stack of thermal oxide and LPCVD nitride. Further examination confirmed that high carrier recombination is due to stress induced by the LPCVD nitride on the peaks and valleys of the textured surface. Use of PECVD nitride instead of LPCVD nitride as an antireflection layer avoids the degraded carrier lifetime caused by the textured surface. Therefore, PECVD nitride should be a good substitute for constructing the oxide-nitride stacks of our future ABC cells.

Keywords: All-back-contacted silicon solar cells; texturing; PCD; LPCVD; PECVD

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1. Introduction

As part of a collaboration between the leading PV manufacturer Trina Solar and the Solar Energy Research Institute of Singapore (SERIS) [2], the Australian National University (ANU) is working on the development of 16-cm^2 all-back-contact (ABC) silicon solar cells on n-type wafer substrates (FZ and CZ). These 16-cm^2 laboratory-sized cells are targeted to reach an efficiency of 23.5% within two years of project commencement (February 2011).

All-back-contact cells were first proposed in 1975 by Schwartz and Lammert of Purdue University for concentrator applications [3, 4]. Research on ABC cells was further carried out by Sandia [5, 6] and Stanford University [7, 8]. SunPower was established in 1985 to commercialise the Stanford developed technology and in 2010 reported efficiencies of large-area solar cells (155.1 cm^2) of up to 24.2% in a commercial production environment [9]. ISFH in partnership with Q-Cells is developing ABC cells through laser-assisted means, and have reported 21% one-sun efficiency [10]. University of Delaware is developing heterojunction ABC cells by low-temperature processing, and they have achieved open-circuit voltages (V_{oc}) as high as 691 mV [11].

The primary advantages of ABC solar cells include: elimination of shading loss associated with front metal grid; no restrictions on the rear side metal area coverage; a front surface which can be optimised solely for passivation and anti-reflection properties; easy-to-implement rear optics and light trapping; simpler cell interconnecting system; and easy adoption of n-type Si, whose lifetime is less susceptible to metal and oxygen impurities. Despite the many advantages, ABC cells require high-lifetime silicon wafers, excellent front surface passivation, and the successful combination of many intricate processing steps in order to realise their high-efficiency potential. At ANU, a modest efficiency has already been achieved for planar ABC silicon solar cells [1]. In the present paper, we report on the progress of further developments (such as inclusion of texturing) of our ABC silicon solar cells, aiming for higher efficiencies in the short term. We also include studies of a two-diode model fit, reflectance measurement, spectral response analysis and photoconductance decay (PCD) measurements that were made to identify the losses associated with the textured ABC cells.

2. Device Structure

A schematic representation of our textured ABC silicon solar cells is shown in Fig. 1. The cell substrate has a final thickness of approximately 200 µm. Random pyramid texturing together with a stack of thermal oxide and LPCVD nitride are at the front surface to minimise the reflectance, improve light trapping and achieve effective surface passivation. The presence of light phosphorus diffusion at the front surface minimises the surface recombination rate further. At the rear surface, n^+ BSF and p^+ emitter are formed in an interrupted interdigitated format between opposite diffusions (n^+ and p^+), with a pitch of 1550 µm and an n^+ area fraction of 25%. Vacuum evaporated Al (~1.5 µm) makes contact to the BSF and emitter regions via point contacts through the rear oxide/nitride stack, to maximise the rear surface passivation.

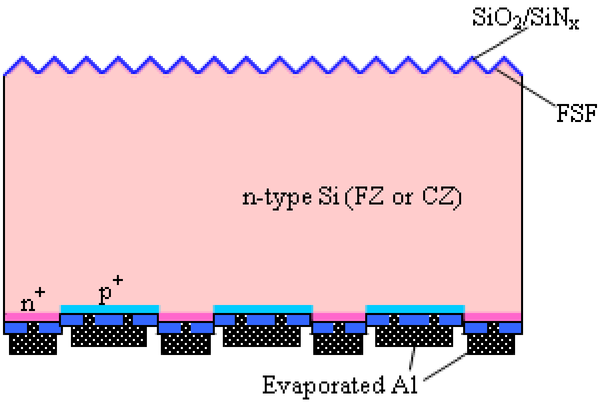

Fig. 1. Schematic structure of our textured ABC silicon solar cell.

3. Cell Development

The fabrication process of the textured ABC cells (this paper) is similar to that of planar ABC cells [1], different only in the simple insertion of a texturing step. Fig. 2 compares the process flows of these cells to the planar cells. The starting material of the cells are ~1 Ωcm 300 micron thick <100> n-type float-zone (FZ) and Czochralski (CZ) wafers. First, the wafers are saw damage etched and thinned down to 200 microns. Then they receive a heavy phosphorus diffusion (n^+) on both surfaces (front and rear), followed by in-situ oxide growth. Next, the wafers undergo single-sided oxide etching on the front, after which the exposed n^+ diffusion is etched off completely. Random pyramid texturing is then created on the front, followed by a light phosphorus diffusion (FSF). A thick masking oxide is grown on both sides, and windows for the p^+ emitters at the rear surface are formed by lithographic means. The n^+ diffusion in the emitter regions is then removed in TMAH at 85°C for 2-3 minutes, followed by the p^+ emitter diffusion. The masking oxide is then removed, and a stack of thermal oxide and LPCVD nitride is grown on both surfaces for passivation and anti-reflection purposes. The metallisation procedure begins with the formation of a regular array of point contact openings in the rear dielectric stack, followed by a blanket Al (~1.5 µm) evaporation on the cells' rear. The metal between the n^+ and p^+ regions is then etched off by photolithographic patterning, forming interdigitated fingers. Finally, the cells are heat treated ("baked") and then diced out of the host wafer into 4 x 4 cm^2 pieces.

4. Results and Characterisations

After fabrication, the cells' one-sun I-V curves were measured using an in-house flash tester [12]. Table 1 shows the main light I-V parameters, from which it is clear that there is no significant difference in performance between FZ and CZ samples. Despite the incorporation of the random pyramid texture, the J_{sc} of the textured cells became poorer than that of previous cells fabricated with planar front surface, which were reported with an average J_{sc} of 34.9 mA/cm^2 [1]. This led us to believe that the front side passivation scheme on the textured surface is less than ideal.

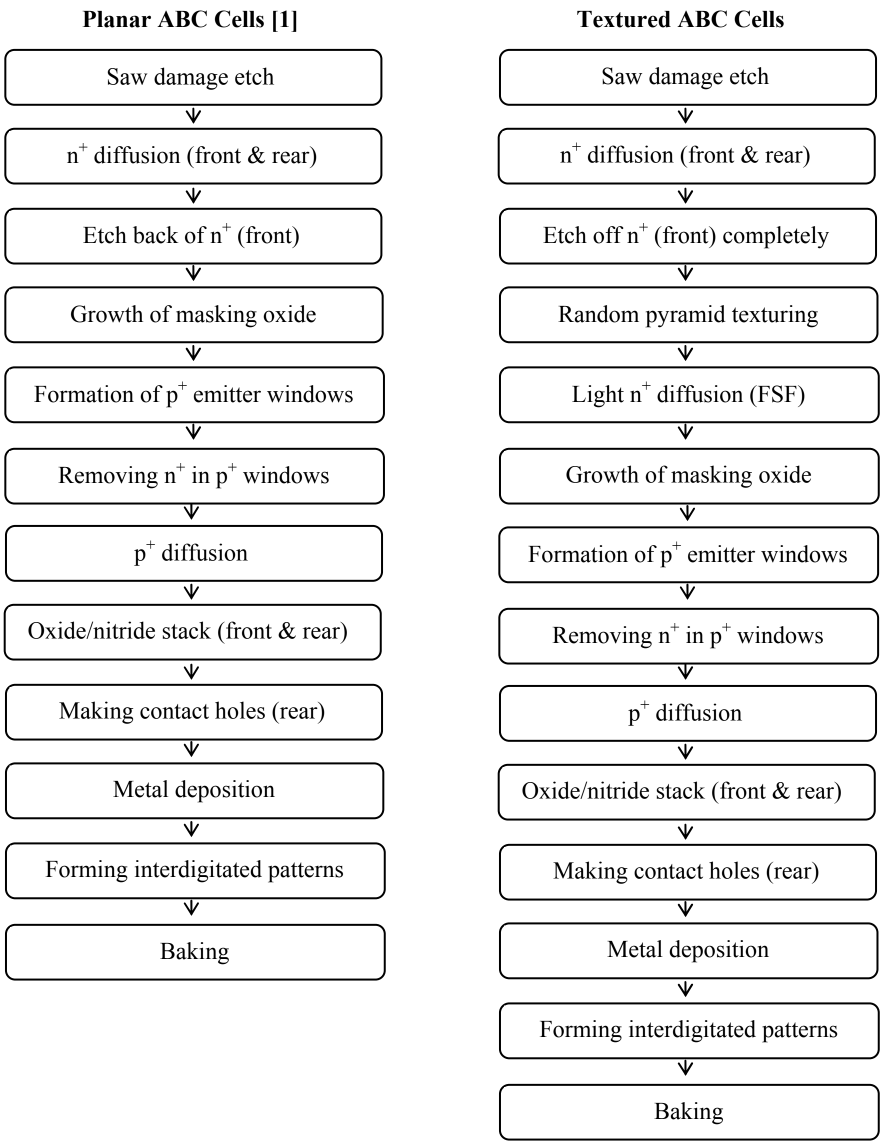

Fig. 2. Fabrication process flow of textured and planar [1] ABC cells.

Table 1: Electrical parameters of textured ABC cells measured under one-sun illumination intensity.

	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF	Eff (%)
Text-Cell1 (CZ)	661	32.1	0.770	16.4
Text-Cell2 (CZ)	663	32.3	0.768	16.5
Text-Cell3 (FZ)	666	32.9	0.774	16.9
Text-Cell4 (FZ)	665	32.9	0.767	16.8

In order to pinpoint the root cause of the low short-circuit current densities, the measured current-voltage curves of the textured cells in the dark (dark I-V) were fitted to the two-diode model using Eq. (1) to further extract parameters such as saturation current densities due to recombination at the surfaces and the bulk (J_{01}), and those due to recombination in the space charge regions of the p-n junctions (J_{02}); shunt resistance (R_{sh}); and dark series resistance (R_{s-dark}) as shown in Fig. 3. In Eq. (1) V is the sense voltage and J is the source current density of the cell measured in the dark.

$$J_{2-diode\_fit} = J_{01}\left(e^{\frac{q(V-JR_s)}{kT}} - 1\right) + J_{02}\left(e^{\frac{q(V-JR_s)}{2kT}} - 1\right) + \frac{(V - JR_s)}{R_{sh}} \quad (1)$$

Based on the fitting of measured dark I-V curves, it is found that the J_{01} of the textured cells are significantly higher than those of the previously reported planar cells [1], while the rest of the parameters – J_{02}, R_{sh} and R_{s-dark} – are similar (Table 2). These high values of J_{01} indicate that a higher surface and/or bulk recombination could be present in the textured ABC cells.

Table 2: Parameters extracted from fitting of the dark I-V curves of the planar and textured cell of Fig. 3.

	J_{01} (fA/cm^2)	J_{02} (A/cm^2)	R_{sh} (kΩ.cm^2)	R_{s-dark} (Ω.cm^2)
Planar cell	105	2.2×10^{-9}	98	0.25
Textured cell	223	1.9×10^{-9}	115	0.28

It is also essential to compare the textured and planar ABC cells in terms of their optical properties. While both types of cells are coated with a thin passivation oxide and LPCVD nitride antireflection coating (ARC) on the front side, the textured cells should have lower reflectance and significantly higher generation current. Figure 4 shows the reflectance of the two cell types in the spectral range of 300 – 1200 nm. Evidentially, the textured cells have significantly improved reflectance (two-fold reduction in reflectance) across the entire spectrum as compared to planar cells, indicating that the texturing improves the optics significantly.

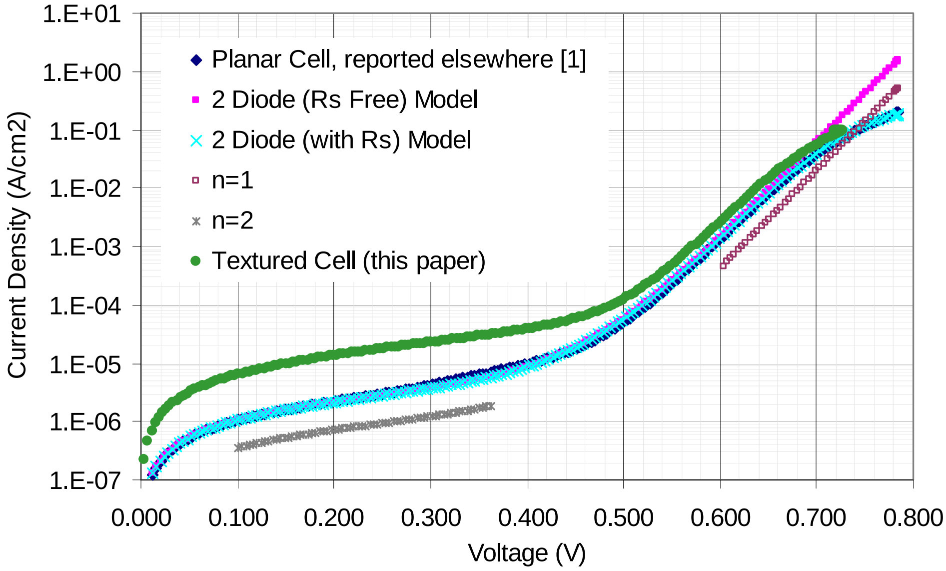

Fig. 3. Measured dark I-V curve of a planar and a textured ABC cell, as well as several calculated dark I-V curves (see legend).

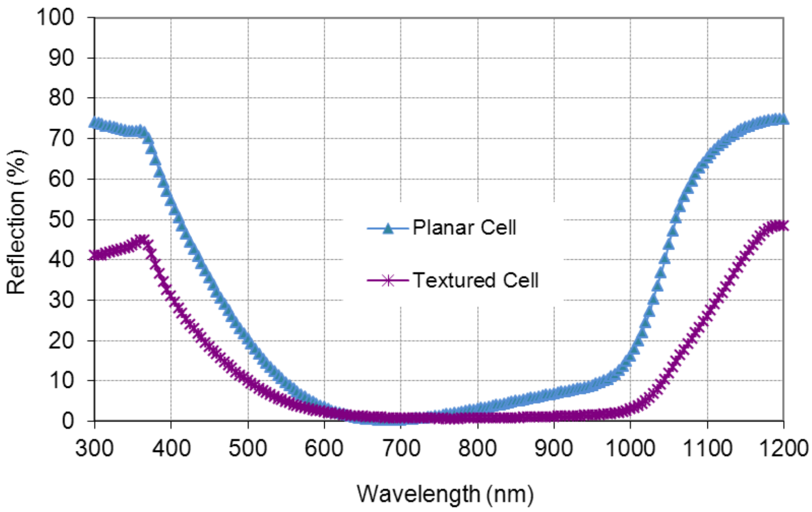

Fig. 4. Measured reflectance of textured and planar [1] cells.

Based on the reflectance of textured ABC cells, the external quantum efficiency (EQE) and the internal quantum efficiency (IQE) were modelled to estimate the collection efficiencies. By matching the measured J_{sc} to those derived from the modelled EQE, we infer that the textured cells have poor carrier collection efficiency of just 81% (spatially averaged across the cell), with an equivalent J_{sc} of 32.9 mA/cm^2 (Fig. 5).

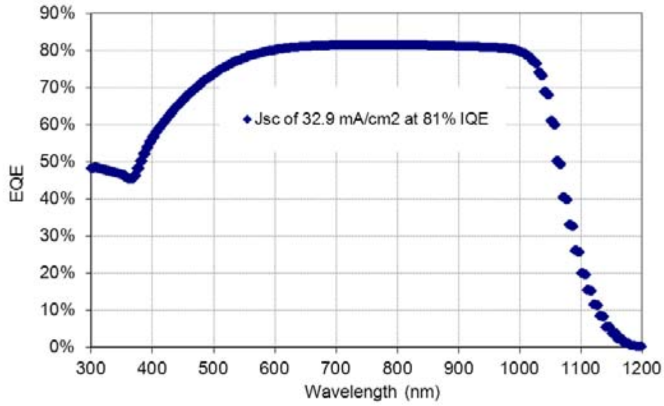

Fig. 5. Modelled EQE of the textured ABC cells based on the measured reflectance.

The poor carrier collection efficiency was further investigated by processing planar and textured samples concurrently in a series of cell fabrication experiments, and by in-situ monitoring of the effective carrier lifetime at an injection level of 1×10^{15} cm^{-3}. As shown in Fig. 6, post-oxidation carrier lifetimes of textured and planar samples were almost the same, but following the LPCVD nitride deposition (used as an ARC) the carrier lifetime of the textured sample was degraded substantially, while that of the planar sample remained almost unchanged. One possible reason for the carrier lifetime degradation of textured samples following the LPCVD nitride growth is stress induced by the LPCVD nitride on the peaks and valleys of the textured surface, as large tensile residual stress is known to be present in LPCVD nitride film [13, 14]. Another possibility is a limited passivation quality by the LPCVD nitride on <111> planes of the textured surface; however, this is unlikely because the surface passivation is mainly provided by the thin thermal oxide underneath the nitride film.

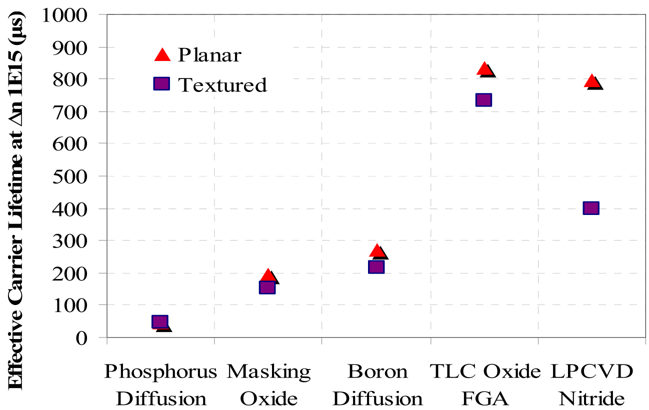

Fig. 6. Measured effective carrier lifetime of textured and planar samples at various stages of the solar cell fabrication sequence.

To further assess the passivation quality of the oxide-nitride stack system, we coated thin oxide passivated textured samples (undiffused) with PECVD and LPCVD nitride layers. Following the deposition of nitride layers, the samples underwent forming gas annealing (FGA) at various annealing temperatures. High carrier lifetime across the entire measured range of injection levels was observed for textured samples with PECVD nitride following the FGA, but the same was not observed for samples with LPCVD nitride. This investigation confirms that use of LPCVD nitride as an ARC layer on textured samples introduces high carrier recombination and PECVD nitride is a better alternative to LPCVD nitride as an ARC layer for the textured samples (Fig. 7), as the PECVD nitride has a lower film density than the LPCVD nitride [13, 14].

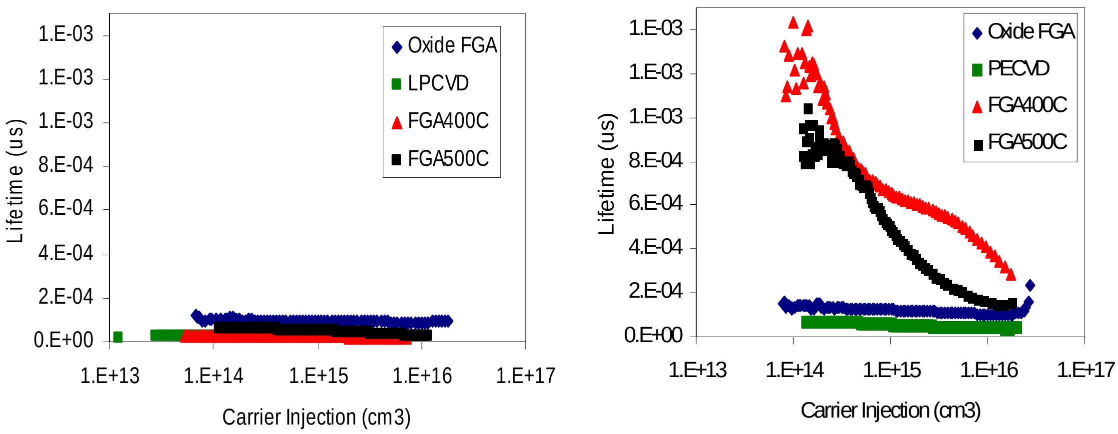

Fig. 7. PCD measurement of samples deposited with LPCVD and PECVD nitride as ARC layers.

5. Conclusion

After producing planar ABC cells with promising device characteristics, additional developments such as incorporation of front side texturing, increasing the metal coverage at the rear to lower the series resistance, and making smaller pitches for the interdigitated n^+ and p^+ diffused fingers are in progress. Random pyramid texturing has improved the optics of the ABC cells significantly, leading to a two-fold reduction in reflectance across the 300 – 1200 nm spectral range. However, on the device level the texturing did not translate into higher J_{sc}, but instead led to inferior overall performance compared to the planar ABC cells. J_{01} values extracted from the dark I-V characteristics of textured cells were also higher than the values of the previously reported planar cells. EQE modelling based on the measured reflectance data demonstrates that the textured ABC cells have a poor carrier collection efficiency of just 81% (spatially averaged across the entire front surface of the cells). Further characterisation based on PCD measurements revealed that the use of LPCVD nitride as an ARC layer, deposited on top of a thin thermal oxide, enhanced the front surface recombination, possibly due to stress induced by LPCVD nitride on the sharp peaks and valleys of the textured surface. Use of PECVD nitride as an ARC layer appears to be a better alternative.

Acknowledgements

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